Technical Integration Strategies for Distributed Energy Resources through Virtual Power Plants and Cooperative Microgrids

Estrategias de Integración Técnica de Recursos Energéticos Distribuidos mediante Centrales Eléctricas Virtuales y Microrredes Cooperativas

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Abstract

This research proposes a methodology to facilitate the technical integration of Distributed Energy Resources through cooperative microgrids and the Virtual Power Plants concept, promoting the transition from centralized (Top-Down) models to decentralized (Bottom-Up) architectures. This approach addresses the challenges faced by conventional power systems experiencing an increasing penetration of distributed generation. To this end, a mathematical optimization model was developed to coordinate two microgrids based on the IEEE 9-bus test system. The proposed methodology was validated using CPLEX optimization algorithms implemented in GAMS and technical simulations conducted in DIgSILENT PowerFactory.

The results demonstrate that coordinated operation among distributed energy units contributes to the overall energy balance and reduces dependence on backup thermoelectric generation. Furthermore, the findings confirm that the strategic integration of distributed generation enhances the reliability and resilience of the power system under realistic demand conditions and the stochastic nature of renewable generation.

Index terms— Distributed Energy Resources, Distributed Generation, Microgrids, Optimization, Virtual Power Plant.

Resumen

Esta investigación propone una metodología para facilitar la integración técnica de los Recursos Energéticos Distribuidos, a través de microrredes cooperativas y el concepto de una Central Eléctrica Virtual, promoviendo la transición desde modelos centralizados (*Top-Down*) hacia arquitecturas descentralizadas (*Bottom-Up*). Este enfoque aborda los desafíos que enfrentan los sistemas eléctricos convencionales ante una creciente penetración de la generación distribuida. Con este propósito, se desarrolló un modelo matemático de optimización para coordinar dos microrredes basadas en el sistema de prueba IEEE de 9 barras. La metodología propuesta fue validada mediante algoritmos de optimización CPLEX implementados en GAMS y simulaciones técnicas realizadas en DIgSILENT PowerFactory.

Los resultados demuestran que la operación coordinada entre unidades energéticas distribuidas contribuye al balance energético global y reduce la dependencia de la generación termoeléctrica de respaldo. Asimismo, los hallazgos confirman que la integración estratégica de la generación distribuida fortalece la confiabilidad y la resiliencia del sistema eléctrico frente a patrones reales de demanda y a la naturaleza estocástica de la generación a partir de fuentes de energía renovable.

Palabras clave— Centrales Eléctricas Virtuales, Generación Distribuida, Microrredes, Optimización Energética, Recursos Energéticos Distribuidos.

Recibido: 29-04-2026 Aprobado tras revisión: 16-07-2026
Forma sugerida de citación: Sarmiento-Vintimilla, J.; Goercke-Abad, W.; Romero, R. (2026). "Technical Integration Strategies for Distributed Energy Resources through Virtual Power Plants and Cooperative Microgrids". Revista Técnica ***"energía"***. No. 23, Issue I . Pp. 79-90
ISSN On-line: 2602-8492 - ISSN Impreso: 1390-5074
Doi: https://doi.org/10.37116/revistaenergia.v23.n1.2026.761

1. INTRODUCTION

1.1. Problem Identification

In recent decades, power systems have undergone a significant transformation driven by the increasing penetration of Distributed Energy Resources (DERs) and stochastic renewable energy technologies. This transformation is motivated by both the need for decarbonization and the pursuit of greater resilience and operational efficiency. However, the transition from centralized schemes to decentralized architectures introduces new challenges related to the operation, control, and operational planning of power systems.

Traditionally, power system operation has relied on hierarchical Top-Down centralized models, in which large-scale power plants supply demand through unidirectional power flows. In contrast, the widespread integration of DERs, including photovoltaic systems, wind generation, small hydropower plants, and Battery Energy Storage Systems (BESS), introduces bidirectional power flows and significantly increases the complexity of operational coordination. This challenge is further intensified by the intermittent and stochastic nature of renewable energy sources, making it more difficult to achieve an efficient dispatch while maintaining system security.

In general, power systems worldwide have demonstrated the need to enhance their flexibility and adaptive capability to cope with scenarios characterized by high variability in renewable generation. In countries such as Brazil, Colombia, and Ecuador, drought events associated with climate change further compromise system security, particularly due to the high dependence on hydropower generation. This situation highlights the need to develop complementary energy alternatives that are properly integrated into power system planning and operational requirements.

In this context, DERs have emerged as a strategic solution to address these challenges. In the Ecuadorian power system, the contribution of distributed generation has historically been limited. However, the recent energy crisis, driven by the country's strong reliance on hydropower and the severe droughts experienced in recent years, has accelerated the deployment of DERs across the residential and industrial sectors, as illustrated in Fig. 1 [1].

Despite this rapid growth, DERs are generally not directly managed by the system operator. Their contribution is typically restricted to supplying energy whenever the primary energy resource is available, rather than responding to the operational requirements of the power system. In the literature, this limitation is commonly referred to as a lack of technical visibility, which constitutes a fundamental prerequisite for the effective technical integration of DERs into modern power systems.

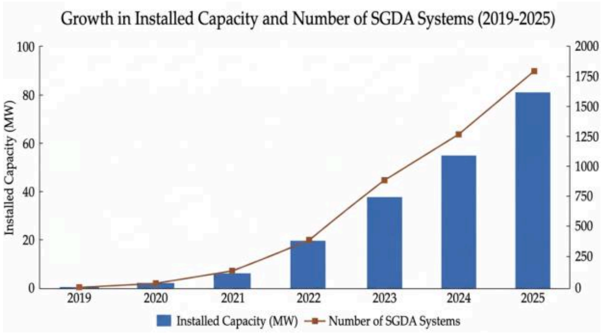

Figure 1: Evolution of Distributed Generation in Ecuador

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Considering the high vulnerability of the power system arising from the aforementioned factors, this paper proposes a mathematical optimization model that provides both technical visibility and controllability of DERs through the Virtual Power Plant (VPP) concept. The proposed approach enables the transition from a conventional Top-Down power system, where operational decisions are made in a centralized and unidirectional manner, to a Bottom-Up architecture, as illustrated in Fig. 2.

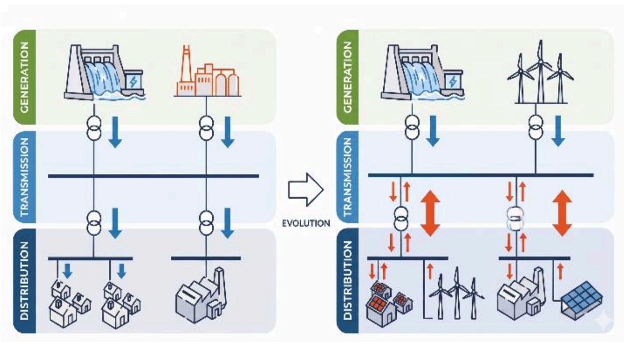

Figure 2: Top-Down vs Bottom-Up architecture

A VPP is an aggregation platform that coordinates the operation of multiple DERs to optimize their collective performance and provide grid services as if they constituted a single generating unit. The individual resources are interconnected through communication and control infrastructures, enabling coordinated operation under a common supervisory framework. In the proposed methodology, an aggregation agent is responsible for ensuring the controllability and coordinated dispatch of DERs while providing the technical visibility required by the system operator, as shown in Fig. 3. Furthermore, because a VPP is not constrained by the geographical location of its constituent resources, it represents a promising solution for achieving efficient coordination among cooperative microgrids.

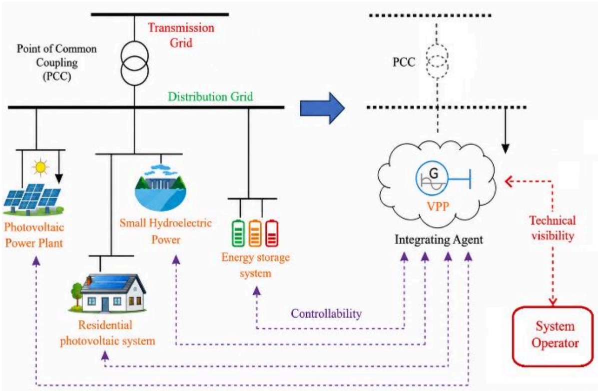

Figure 3: Virtual Power Plant Concept

1.2. Literature Review

The increase in the penetration of renewable energy sources in modern electrical systems has not only opened new opportunities but also significant challenges for the operation, planning, and sustainability of traditional electrical grids. As decentralized generation paves the way for models based on DERs, the necessity arises to implement innovative power control systems that ensure efficient and resilient management. Many studies have analyzed the progress in technologies such as VPPs, microgrids, and energy communities, proposing new optimization models, architectures, and strategies [2].

In the current energy transition scenario, VPPs have emerged as a technical solution designed to manage complex and ever-growing modern electrical systems. By operating as an aggregation agent, VPPs coordinate different DERs under a single administrative profile. This not only allows low-power distributed resources which are often geographically dispersed to gain visibility for the system operator, but also opens up new opportunities for commercialization in wholesale energy markets. The added value of VPPs lies in their architecture, which contrasts with traditional systems and, by doing so, allows for resource coordination from the consumer level and supports microgeneration sites. It is also noted that a VPP provides greater flexibility to the system through control and prediction algorithms that work as a counterweight to the unpredictability of stochastic renewable non-conventional resources, while offering ancillary services such as frequency regulation, voltage support, and power reserves. [3].

In this context, fractal and holonic architectures stand out for their capacity to improve the operational flexibility and scalability of the grid, while allowing advanced control systems to manage bidirectional power flow [4]. Along these lines, fractal architectures have been formalized using the FOCUS system, with the goal of improving scalability and flexibility in both microgrids and VPPs [5]. In parallel, the term "holonic" distinguishes itself by referencing the structural, static organization of a management system, while the term "fractal" relates to its dynamic behavior [6].

The fractal principle, although relatively new, has allowed for significant advancements in distributed generation; it enables electrical generation near consumer areas using renewable resources, such as solar energy. This scheme not only contributes to reducing power losses but also improves the resilience and reliability of the grid. Nevertheless, the transition toward this model comes with its own challenges: infrastructure traditionally designed for centralized production must be adapted to numerous small-scale generation units, bidirectional power flow management, maintaining the balance between generation and demand, and ensuring a fail-safe grid. Fractal modeling, based on self-similarity, offers advantages such as scalability, energy efficiency, and predictable behavior [7] .

Various authors highlight difficulties in the integration and optimization of renewable energy sources. Control systems address issues related to intermittency and volatility derived from these resources, whose stochastic nature could lead to forecasting errors, suboptimal operation, and resource waste [8]. For the optimal planning of these resources, mathematical techniques are employed, such as Linear Programming (LP) and Mixed-Integer Nonlinear Programming (MINLP), as well as different stochastic programming models that support VPPs in power dispatch and market participation under uncertainty [9].

Within this operating scheme, for alternative energy integration models to be viable, it is mandatory to analyze the technical response capacity of the virtual power plant. Sarmiento et al. introduces an evaluation framework based on several operational flexibility metrics such as capacity range, ramp rates, and power reserves applied to both active and reactive power [10]. Complementarily, Ulbig defines mathematical metrics to evaluate operational flexibility within the electrical system [11]. The management of said flexibility is not only fundamental to the internal optimization of the VPP but also lays the foundation for multisystem cooperation [12] [13].

Table 1 presents a comparison of the main works related to the integration of distributed energy resources through VPPs, cooperative microgrids and fractal architectures.

Table 1: Comparison of related works on the integration of DERs using VPPs

Author/Year	Main focus	Main contribution	Limitations
Vasquez et al. (2010) [2]	Hierarchical control of microgrids	Proposes control strategies for distributed energy management in microgrids.	Limited focus on multi-microgrid coordination.
Bytschkow (2015) [5]	Fractal architectures for Smart Grids.	Develops principles of composition and scalability for intelligent grids with a fractal approach.	It does not include explicit energy optimization.
Ulbig (2015) [11]	Operational flexibility of the electrical system.	Defines mathematical metrics to evaluate operational flexibility in electrical systems.	It is not specifically focused on VPPs.
Molotov et al. (2018) [13]	Microgrid modeling with renewable energy.	Analyzes operational behavior of microgrids with renewable sources.	Limited focus on large-scale coordination.
Kiriakos and Zaro (2021) [12]	Microgrid design for photovoltaic systems.	It focuses on grid-linked systems for photovoltaic energy management.	They lack comprehensive approaches to load reduction.
Sarmiento et al. (2022) [3]	Energy management and operation of VPP.	It defines VPPs as DER aggregators to coordinate resources and participate in markets.	It defines the coordination strategies for virtual power plants and addresses the bottom-up concept. However, it does not analyze optimization models for the dispatch of DERs.
Sarmiento et al. (2024) [10]	Operational flexibility in VPP.	Quantify the energy flexibility of DERs using metrics under uncertainty.	It focuses on flexibility metrics but does not develop a coordination architecture for DER integration.
Al Issa et al. (2025) [7]	Grid model based on fractal-cluster principle.	A fractal architecture can strengthen the capacity to adapt to critical conditions.	Centralized infrastructures must adapt to bidirectional flows.

1.3. Research Contributions

The present work contributes to the advancement and development of strategies to facilitate the technical integration of distributed energy resources through the development of an innovative framework that combines the concepts of cooperative microgrids and VPPs. Unlike traditional frameworks, which present limitations in scalability, multisystem coordination, and operational efficiency, this research simultaneously addresses these challenges from a systemic and adaptable perspective:

- An energy management architecture based on the cooperative microgrids is proposed, which allows for the structuring of decentralized electrical systems under hierarchical schemes. This approach facilitates scalability and interoperability between multiple microgrids, promoting an effective transition from centralized models to bottom-up configurations, which are more in line with modern electrical systems.
- A mathematical optimization model is developed that manages cooperative microgrid operation through a VPP acting as an aggregation agent. This model simultaneously integrates diverse generation sources both renewable and conventional with BESS, allowing for efficient power dispatch that maximizes the use of renewable resources while minimizing dependency on backup generation.
- A virtual coupling scheme enables energy cooperation between microgrids without the need for physical connection between them. This represents a relevant contribution in terms of operational flexibility and cost-effective applicability in real-world systems.
- Finally, the model's validation in an advanced simulation environment using the IEEE 9-bus standard system and considering different operational scenarios demonstrates its technical feasibility and its capacity to contribute to operational stability.

These contributions position the proposed approach as a robust, scalable, and applicable alternative for the efficient integration of DERs in modern electrical systems. The rest of this article is organized as follows: **Section 2** presents the proposed methodology, which includes the system architecture and the formulation of the mathematical model for the VPP. **Section 3** analyzes the results obtained from the operational coordination of DERs. Lastly, **Sections 4 and 5** present the discussion and conclusions derived from this research.

2. METHODOLOGY

With the goal of verifying the applicability of the proposed model in electrical system management, a modular grid topology was configured applying the IEEE 9-bus standard system as a reference for the operational behavior analysis as shown in Fig. 4. [14].

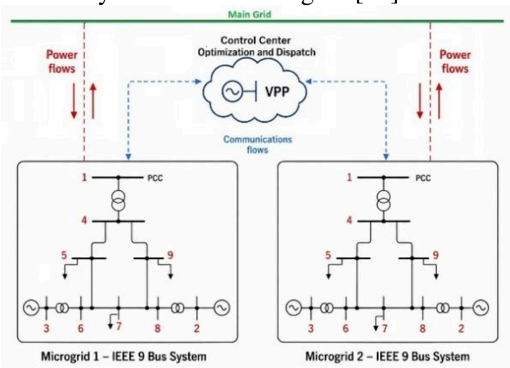

Figure 4: IEEE 9-bus standard topology

2.1 Case Study Grid Architecture

The studied system was designed comprising different sections that interact with one another.

- Main Grid: It is represented as an infinite bus that performs a dual role. From a technical standpoint, it serves as a reference for both voltage and frequency to ensure system stability. From a commercial perspective, on the other hand, it operates as the exchange node where the VPP delivers its firm, constant power block, absorbing the continuous power supply and generating revenue from the stability services provided by the microgrids.
- Cooperative Microgrids: Two independent microgrids were developed (MG1 and MG2); both integrate distributed generation and are connected to the main grid for power supply.

Fig. 5 shows the general architecture of the proposed system, composed of two microgrids interconnected by a slack bus that acts as a reference node for power exchange with the main grid.

With the ultimate goal of guaranteeing the feasibility and reliability of the model, real operational records provided by the company ELECAUSTRO S.A. (Ecuador's public electricity generation company), were used. Specifically, power generation data from the Huascachaca wind and solar farm were utilized to develop the statistical profiles for the model. Although both microgrids share the same general structure, their distributed energy resources are not identical. Therefore, it is necessary to clearly define the location and capacity of the DERs installed in each microgrid.

MG1 contains photovoltaic generation located at buses b2, and b3 with a capacity factor of 17% and 150 kW. Wind generation is distributed at buses b3, b4, b5, b6, and b7 with a capacity factor of 28% and 20 MW. MG1 includes one hydroelectric unit located at bus b8, with a nominal power of 20 MW and a maximum daily available energy of 240 MWh. The storage system of MG1 is composed of two battery energy storage units located at buses b5 and b6, each one with 10 MWh of energy capacity and 5 MW of maximum charging and discharging power. Therefore, MG1 has a total storage capacity of 20 MWh and a total charge/discharge power capacity of 10 MW. Finally, MG1 includes two thermal backup units located at buses b2 and b3, each one with 20 MW of nominal power, giving a total thermal backup capacity of 40 MW.

MG2 contains photovoltaic generation located at buses b2, b3, b4, b5, b6, and b7 with a capacity factor of 16,5% and 355 kW, wind generation in MG2 is distributed across buses b2 to b9 with a capacity factor of 31% and 36 MW. Hydroelectric generation in MG2 is represented by three hydroelectric units located at buses b5, b7, and b8. Each unit has a nominal power of 20 MW, giving a total hydroelectric capacity of 60 MW. The maximum daily available hydroelectric energy in MG2 is 840 MWh. The battery storage system of MG2 is composed of two battery units located at buses b5 and b6, each one with 12 MWh of energy capacity and 5 MW of maximum charging and discharging power. Therefore, MG2 has a total storage capacity of 24 MWh and a total charge/discharge power capacity of 10 MW. Finally, MG2 includes three thermal backup units located at buses b2, b3, and b9, each one with 20 MW of nominal power, resulting in a total thermal backup capacity of 60 MW.

The demand profile is also distributed between both microgrids. In MG1, the aggregated demand varies between approximately 8,16 MW and 40,49 MW during the 24-hour horizon. In MG2, the aggregated demand varies between approximately 6,62 MW and 33,08 MW. Therefore, the total VPP demand ranges from approximately 14,77 MW to 73,57 MW. This demand is supplied through the coordinated use of renewable generation, hydroelectric generation, battery storage, thermal backup units, energy imports from the main grid, and cooperation between microgrids.

Simulation Scenarios: Two operational modes were defined to evaluate the impact of the proposed architecture:

A. Disaggregated Operation: In this mode, microgrids MG1 and MG2 operate as completely isolated entities. Each microgrid optimizes its dispatch to minimize its own operational costs without allocating the surplus of one grid to cover the deficit of the other. Any energy imbalance is addressed by purchasing energy directly from the main grid.
B. Coordinated Operation: By enabling joint optimization, the model seeks a global system balance, allowing the energy injection from one microgrid into the main grid to be recognized as a supply for the other. This results in a more efficient system and minimizes net dependency on external sources.

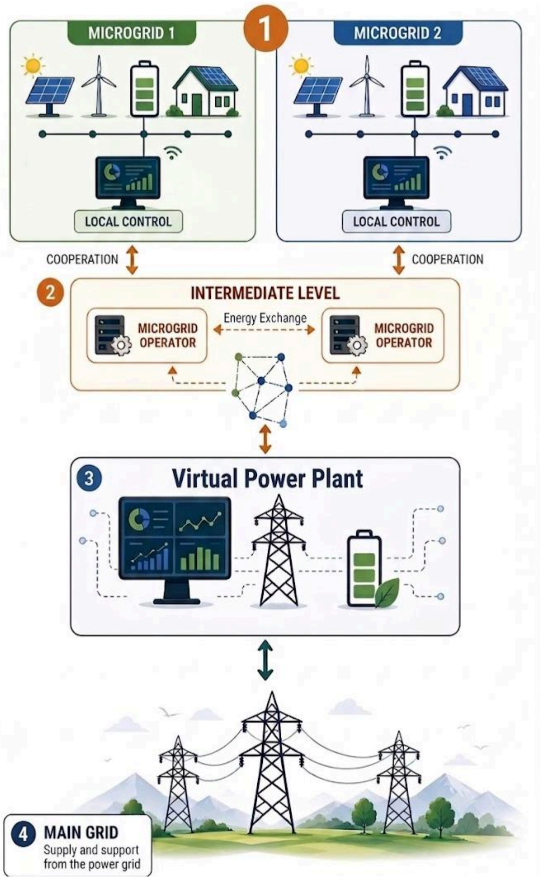

Figure 5: Energy cooperation between microgrids

2.2 Proposed Mathematical Model

The operational coordination of the proposed resources is formulated as a mathematical optimization problem aimed at determining the optimal generation dispatch that satisfies commercial commitments while minimizing the total operating cost, denoted by Z. The objective function comprises the following cost components: Z_R, the cost associated with renewable energy generation (solar and wind); Z_H, the operating cost of hydropower generation; Z_B, the cost associated with the operation of the BESS, including charging and discharging processes; Z_T, the operating cost of thermal generating units, including generation and start-up/shut-down costs; Z_G, the net cost of energy exchange with the main grid; Z_{EX}, the cost associated with power exchange between microgrids; Z_{OR}, the overall cost of coordinated system operation; and, Z_{CO}, the costs associated with operational constraints and model penalty terms.

$$minZ = Z_R + Z_H + Z_B + Z_T + Z_G + Z_{Ex} + Z_{OR} + Z_{CO} \quad (1)$$

2.2.1 *Virtual Coupling and Power Delivery*

To represent the aggregated operation of the cooperative microgrids, the net power injected by the VPP into the main grid is defined. This magnitude is expressed as the difference between the power exported and imported by the microgrids during each hourly interval:

$$P_{net,h} = \sum_{m \in MG} \left(P^{exp}_{m,h} - P^{imp}_{m,h} \right) \quad (2)$$

where $P_{net,h}$ represents the net power exchanged between the VPP and the main grid at hour h and where the microgrids are represented as $m \in MG$, $P^{exp}_{m,h}$ is the exported power and $P^{imp}_{m,h}$ is the imported power at a period h of time.

For this case scenario, a firm, constant power delivery commitment is imposed on the VPP, such that the net power exported to the main grid maintains a flat profile throughout the entire operational horizon:

$$P_{neto,h} = P^{VPP}_{TGT}, \forall h \quad (3)$$

where, P^{VPP}_{TGT} corresponds to the power delivery target committed to the system operator. In the developed case study, a fixed delivery of 3 MW is adopted for each hour of the planning horizon.

2.2.2 *Export Breakdown:*

With the objective of tracing the energy origin of the power delivered by the VPP, the total export from each microgrid is divided into a renewable component and a thermal component:

$$P^{exp}_{m,h} = P^{exp,Ren}_{m,h} + P^{exp,Therm}_{m,h}, \ \forall m, h \quad (4)$$

$$P^{exp,Ren}_{m,h} = \sum_b P^{PV,exp}_{m,b,h} + P^{W,exp}_{m,b,h} + P^{H,exp}_{m,b,h} + P^{dis,exp}_{m,b,h} \quad (5)$$

where $P^{exp,Ren}_{m,h}$ represents the fraction of exports originating from renewable resources and storage, composed as follows: $P^{PV,exp}_{m,b,h}$ represents all photovoltaic power generation exports, $P^{W,exp}_{m,b,h}$ represents all wind power generation exports, $P^{H,exp}_{m,b,h}$ represents all hydropower generation exports and $P^{dis,exp}_{m,b,h}$ represents the batteries' discharge power exports on a specified bus b, while $P^{exp,Therm}_{m,h}$ represents the fraction associated with thermal generation exports. This decomposition allows for verifying, within the results analysis, whether the delivery committed to the main grid is covered by renewable generation or if it requires thermal support during specific hours.

2.2.3 *Operational Constraints*

Nodal Power Balance

$$P^{PV,exp}_{m,b,h} + P^{W,exp}_{m,b,h} + P^{H,exp}_{m,b,h} + P^{dis}_{m,b,h} + P^{T}_{m,b,h} + P^{imp}_{m,b,h} + P^{coop,in}_{m,b,h} - \sum_l P_{m,b,l,h} \left(From_{m,b,l} + To_{m,l,b} \right) + LS_{m,b,h} = D_{m,b,h} + P^{ch}_{m,b,h} + P^{exp}_{m,b,h} + P^{coop,out}_{m,b,h} \quad (6)$$

This equation represents the systems nodal balance where $P^{T}_{m,b,h}$ is the total power produced by thermal backup generators, $P^{imp}_{m,b,h}$ represents all power imported from the main grid and $P^{coop,in}_{m,h}$ is the power received from the other microgrid as cooperation.

$\sum_l P_{m,b,l,h}(From_{m,b,l} + To_{m,l,b})$ stands for the active power flow through transmission lines (l) for each microgrid in each bus in a specified period of time. $LS_{m,b,h}$ represents the load shedding, $D_{m,b,h}$ represents the internal power demand, $P^{ch}_{m,b,h}$ is the power used to charge the batteries, $P^{exp}_{m,b,h}$is the exported power to the main grid, $P^{coop,out}_{m,b,h}$ is the power sent from one microgrid to the other as cooperation for each microgrid in each bus at each period of time.

2.2.4 *Generation Constraints*

Power Limits:

$$P_g^{min} \cdot u_{g,t} \leq P_{g,t} \leq P_g^{max} \cdot u_{g,t} \tag{7}$$

Where P_g^{min} and P_g^{max} are the minimum and maximum capacities at which the generator operates, $u_{g,t}$ is a binary variable used to tell if the machine is on (1) or off (0) and $P_{g,t}$ is the power generation at a period of time t.

Ramp-Up Rate:

$$P_{g,t} - P_{g,t-1} \leq R_g^{up} \cdot u_{g,t-1} + P_g^{max} \cdot (1 - u_{g,t-1}) \tag{8}$$

Ramp-Down Rate:

$$P_{g,t-1} - P_{g,t} \leq R_g^{down} \cdot u_{g,t} + P_g^{max} \cdot (1 - u_{g,t-1}) \tag{9}$$

R_g^{up} and R_g^{down} they indicate how quickly a generator can increase or decrease its power output from a $t-1$ to a t period of time.

2.2.5 *Storage Dynamics*

Energy Balance:

$$SOC_{b,t} = SOC_{b,t-1} + \eta_c \cdot P_{cg,b,t} - \frac{1}{\eta_d} \cdot P_{dis,b,t} \tag{10}$$

$SOC_{b,t}$ represents the state of charge at a specific period of time. η_c and η_d are the charge and discharge efficiencies

Exclusivity Constraint:

$$0 \leq P_{ch,b,t} \leq P_{ch}^{max} \cdot u_{bat,b,t} \tag{11}$$

$$0 \leq P_{dis,b,t} \leq P_{dis}^{max} \cdot (1 - u_{bat,b,t}) \tag{12}$$

$P_{ch,b,t}$ and $P_{dis,b,t}$ represent power charge and discharge, while P_{ch}^{max} and P_{dis}^{max} represent the maximum charge and discharge levels allowed. $u_{bat,b,t}$ is a binary state variable to forbid simultaneous charge and discharge.

Capacity and Boundary Limits:

$$SOC_{b,t=24} \geq SOC_{b,initial} \tag{13}$$

Forces the algorithm to charge the battery to at least its initial levels at the end of the 24-hour operational horizon.

3. RESULTS ANALYSIS

3.1 Scenario 1: Disaggregated Operation:

Initially, the operational behavior of MG1 and MG2 was evaluated in an isolated manner. Under this traditional scheme, the optimization algorithm minimized operational costs independently, forcing each microgrid to satisfy its own demand through local resources. If a power deficit occurred, the microgrid was obligated to buy power from the main grid at market prices or rely on backup thermal generation. Fig. 6 shows the combined operation of the two microgrids to meet demand. In this scenario, there is a need for thermal generation (red bars) and for purchasing energy from the grid (orange bars).

Under this operating scenario, renewable energy sources supply 80.47% of the total demand, with hydropower representing the largest share at approximately 55.42%. The remaining 19.53% of the energy balance is met through backup thermal generation.

Since this scenario lacks a cooperative design, the results highlight the typical inefficiency of distributed generation systems when operating without coordination. This operational case serves as a baseline to later compare the benefits of a coordinated architecture. In qualitative terms, it represents the typical behavior of two isolated microgrids lacking an integration mechanism, where system balance is guaranteed only locally rather than globally.

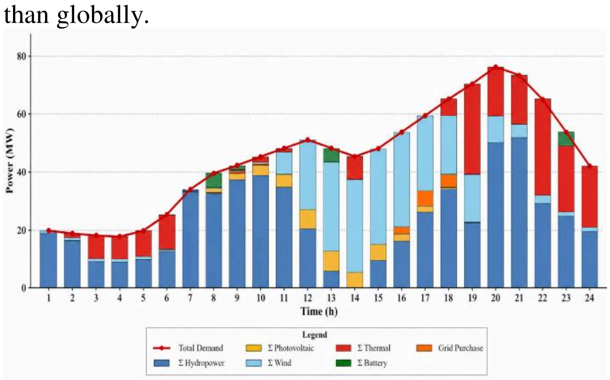

Figure 6. Operation of the system without internal cooperation

3.2 Scenario 2: Coordinated Operation between Microgrids

This scenario enables coordinated cooperation between MG1 and MG2 through the proposed architecture, with the VPP acting as the aggregating agent. Under this configuration, the microgrids cease to operate independently and converge into a single aggregated entity governed by a joint operational scheme. This strategy allows surpluses from one microgrid to cover the deficits of the other, enabling the two grids to function as interconnected parts of a whole. Consequently, this integration provides greater flexibility and maximizes the exploitation of available renewable resources.

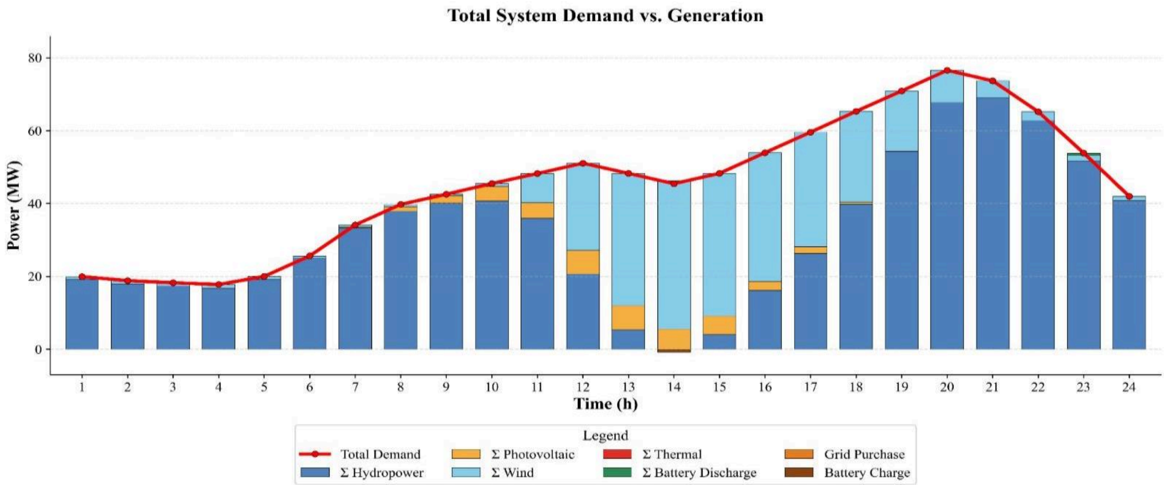

Figure 7: Comparison between total demand and total generation of the coordinated system

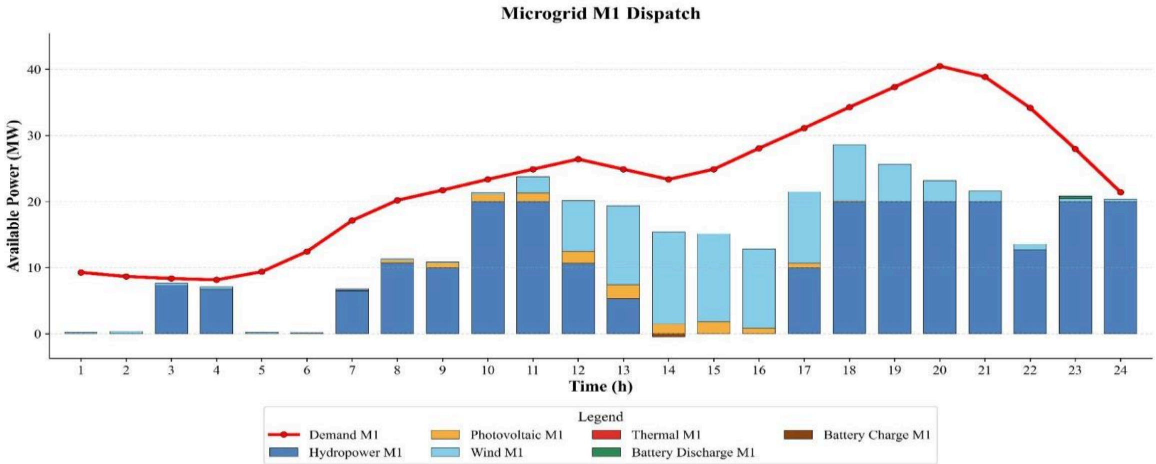

Figure 8: Hourly generation dispatch in microgrid MG1

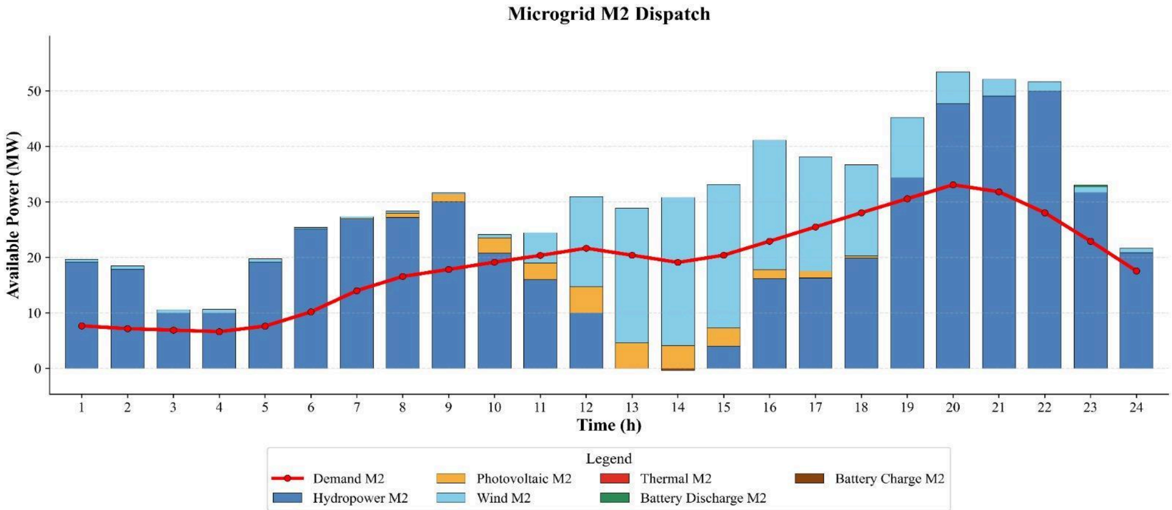

Figure 9: Hourly generation dispatch in microgrid MG2

The comparison between the total demand and the total generation of the system is illustrated in Fig. 7. It can be observed that both magnitudes are equivalent throughout the 24-hour operational horizon, with the exception of the generation peak occurring in t14. These peaks correspond to the periods in which the Battery Energy Storage System is being charged, thereby ensuring an adequate energy balance. Furthermore, it is noted that the total system demand reaches its maximum values in t20, defining the critical period of the operational horizon. This result confirms that the optimization model effectively coordinates all available renewable resources and backup plants to satisfy the aggregated demand, demonstrating that the virtual coupling imposed by the VPP functions correctly.

The hourly dispatch for MG1 is presented in Fig. 8. Individually, this microgrid does not have sufficient renewable generation capacity to satisfy its own demand. Therefore, under the disaggregated operating scenario, it must rely on backup thermal generation and energy imports from the main grid to meet its energy requirements. In contrast, under the proposed cooperative operation framework, the dispatch of MG1 is optimized by exploiting the energy complementarity provided by MG2, thereby avoiding the use of higher-cost energy alternatives. It is observed that during morning hours, there is a significant contribution from wind generation, complemented to a lesser extent by photovoltaic generation and, as the day progresses, by hydroelectric generation. During these periods of high resource availability, the system utilizes the surplus to recharge the BESS, which will be deployed in subsequent periods.

On the other hand, Fig. 9 illustrates the generation dispatch for microgrid MG2. This microgrid has a high installed capacity of renewable energy resources. Under the disaggregated operating scenario, surplus energy must be traded in electricity markets to avoid renewable energy curtailment. However, this approach entails economic risks associated with market participation and depends on effective commercial integration. Since this research focuses exclusively on the technical integration of DERs, the operational flexibility of MG2 is exploited to support the energy deficit of MG1, thereby maximizing the utilization of the available renewable resources. In this case, the significant contribution of hydroelectric generation is notable, acting as a flexible support source to cover the local demand and contribute to the energy cooperation scheme. This strategic management of water resources makes MG2 a key node within the global coordination; since hydroelectric plants possess regulation capacity, they act as a compensation mechanism against the stochastic variability of non-conventional renewable generation, highlighting energy complementarity as a cornerstone of the proposed cooperative model.

Table 2 shows a summary of the most significant quantitative results of the cooperative scenario.

Table 2: Cooperative Microgrid Scenario Results

Parameter	Value	Description
Total Demand	14.77-73.57 MW	Variation in aggregate demand over the 24-hour horizon.
Total Hydroelectric Generation	762,12 MWh	Total hydroelectric generation under the coordinated operation scheme.
Renewable Energy Share	99,94 %	Share of energy supply from renewable sources in the cooperative scenario.
Contribution of Battery Energy Storage Systems (BESS)	0,06 %	Contribution of batteries to the total energy supply in coordinated operation.

3.3 Role of the VPP in the Cooperative Microgrid Operation

VPPs have emerged as an effective strategy to facilitate the technical and commercial integration of DERs into power systems. Their operation relies on an aggregation agent capable of coordinating multiple microgrids, optimizing the available resources, and exploiting the energy complementarity among different generation technologies. However, this study focuses exclusively on the technical benefits that VPPs provide to power system operation rather than on their participation in electricity markets. Although the proposed optimization model aims to minimize operating costs, the primary role of the VPP is to maximize the utilization of renewable energy resources. This objective is achieved through the coordinated dispatch of technologies with near-zero variable costs, such as photovoltaic and wind generation, very low variable costs associated with hydropower, and comparatively high variable costs corresponding to thermal generation and energy imports from the main grid.

The results demonstrate that coordinated microgrid operation significantly improves the overall performance of the system. Although solar and wind generation remained unchanged in both operating scenarios, their utilization increased by 22% due to the reduction of renewable energy curtailment. Furthermore, hydropower production increased from 566,33 MWh to 762,12 MWh over the 24-hour operating horizon, completely eliminating the need for backup thermal generation.

Under the disaggregated operating scenario, 199,56 MWh of backup thermal generation was required to satisfy system demand. These results demonstrate that energy exchange between microgrids enables the system to compensate for energy deficits by utilizing available renewable resources that would otherwise be curtailed, thereby eliminating the dependence on backup thermal generation. Consequently, the share of renewable resources in the energy mix increased from 80,47% in the baseline scenario to 99,94% under cooperative operation, while BESS contributed only 0,06% of the total energy supplied.

Overall, the results demonstrate that coordinated operation transforms independent microgrids into a more robust cooperative energy system. Integrating DERs through a VPP enables more effective utilization of surplus renewable energy, maintains the overall energy balance, and supports sustained energy exports to the main grid while reducing reliance on high-cost backup generation.

Table 3 shows the most significant benefits of the cooperative scenario compared to the disaggregated scenario.

Table 3 : Disaggregated Scenario vs Coordinated Scenario

Performance variable	Disaggregated Scenario	Cooperative Scenario	Impact
Backup thermal generation	199,56 MWh	0 MWh	Complete elimination of thermal backup dependency.
Hydroelectric Generation	566,33 MWh	762,12 MWh	Increase of 195,79 MWh to meet the demand of both microgrids.
Share of Renewable Resources	80,47 %	99,94 %	19,47% increase in the system's energy mix.

Finally, an additional validation stage was carried out in DIgSILENT PowerFactory as part of the proposed methodological framework. The simulation results confirm that the power flow converges under the coordinated operating scheme and that voltage profiles remain within the permissible limits (±5%) at all system buses. In this regard, the validation is not intended to provide a detailed numerical assessment but rather to verify the technical feasibility of the proposed topology under realistic operating conditions. Such analyses constitute an essential step that the VPP operator should perform to ensure the secure and reliable operation of the power system.

In this context, the VPP plays a key role in coordinating DERs, including the indirect management of reactive power. Through the coordinated control of distributed generation, energy storage, and conventional generation units, the VPP contributes to maintaining acceptable voltage levels, improving power flow distribution, and reducing system losses. This capability becomes particularly important in power systems with high penetration of renewable energy resources, where coordinated operation enhances both operational efficiency and system resilience.

4. DISCUSSION

DERs have great potential to contribute to the operation of the electrical system. However, the lack of technical integration means that these units are underutilized. The results of this research imply not only an improvement in operational indicators, but also a change in the way DERs interact with each other and with the main grid. Rather than simply improving operational indicators, coordinated operation fundamentally changes the interaction between DERs and the main grid. The difference between the analyzed scenarios is significant; transitioning from an isolated to a coordinated operation implies moving from local inefficient decisions toward a systemic logic where global benefit takes precedence over the individual. In the disaggregated scenario, the system's behavior reproduces the typical limitations of distributed generation when an effective coordination mechanism is absent.

Each microgrid responds to its own constraints without considering the state of the system as a whole, leading to an inefficient use of available resources. This result is consistent with existing literature, where the lack of integration among DERs typically results in higher operational costs and an unnecessary reliance on backup generation. In contrast, coordinated operation demonstrates that even without physical modifications to the infrastructure, the mere introduction of an intelligent aggregation scheme can substantially change global performance.

One of the most relevant aspects is the model's ability to exploit the energy complementarity among sources. The interaction between wind, solar, and hydroelectric generation, coupled with energy storage support, not only allows for efficient demand coverage but also substantially reduces the use of thermal generation in the case study. This result should be interpreted with caution; while it responds to the specific conditions of the modeled system, it highlights the real potential of coordinated schemes to displace costlier and more polluting technologies when flexibility is adequately managed.

Along these lines, the role of hydroelectric generation as a regulating resource deserves special attention. Far from acting solely as a baseload source, its role within the proposed architecture is closer to that of a dynamic balancing mechanism, capable of compensating for the variability of non-conventional sources. This behavior reinforces the idea that the integration of DERs does not depend exclusively on adding more installed capacity, but rather on the intelligent management of existing resources.

Another outstanding result is the VPP's ability to sustain a constant power delivery to the main grid, despite the inherently variable nature of renewable resources. This finding is particularly significant, as it addresses one of the most frequent criticisms of distributed generation: its perceived inability to provide firm power services. What the model demonstrates is that, under an adequate aggregation and coordination scheme, individual variability can be smoothed at the aggregated level, resulting in more stable and predictable generation profiles.

From a methodological standpoint, the adoption of a cooperative principle introduces a differentiating element compared to conventional approaches. More than a simple hierarchical structure, the proposed scheme suggests an organizational logic in which each level of the system replicates similar operational patterns, thereby facilitating scalability. This is particularly relevant in scenarios where the expansion of DERs does not follow centralized planning but rather responds to local and heterogeneous dynamics. In this sense, the proposed architecture not only solves an immediate technical problem but also provides a conceptual framework for the orderly growth of increasingly distributed power systems.

Nevertheless, it is important to recognize certain limitations of this study. The model focuses on technical integration and does not explicitly incorporate market signals, which could influence the economic viability of operational decisions. Furthermore, while the AC environment validation confirms the electrical feasibility of the dispatch, the real-world implementation of coordination schemes like the one proposed would require more advanced communication and control infrastructures, as well as regulatory frameworks that facilitate the aggregated operation of DERs.

The results suggest that the challenge of integrating distributed resources lies not only in their quantity or diversity but in the system's ability to coordinate them effectively. The evidence presented reinforces the idea that future solutions will not solely involve expanding infrastructure, but rather redefining the control and operational architectures that allow for maximizing the exploitation of available flexibility.

5. CONCLUSIONS

The development of this work allows for the extraction of a central idea that permeates the entire research: the effective integration of DERs depends not only on their technological incorporation, but also on the way they are organized and coordinated within the power system. Under this premise, the proposed architecture based on the use of a VPP proves to be a coherent alternative to the current needs of increasingly decentralized systems.

One of the most consistent findings is the substantial difference between operating microgrids in isolation versus under a coordinated scheme. While the former reproduces known inefficiencies such as greater dependence on the main grid and unnecessary use of backup generation, the latter demonstrates that energy cooperation enables a more intelligent exploitation of available resources. This improvement is not marginal but structural, as it transforms the operational logic from a local approach to a global perspective.

Furthermore, the model confirms that the aggregation of DERs can overcome one of the primary barriers attributed to renewable energy: the variability and stochasticity of the primary resource. Far from representing an insurmountable limitation, the results show that, through coordination and storage, it is possible to construct stable and reliable generation profiles. The ability to maintain a constant power delivery to the main grid is, in this sense, a particularly relevant outcome, as it brings distributed systems closer to the operational standards traditionally required of conventional generation.

Another aspect worth highlighting is the role of energy complementarity. The interaction between different technologies, especially between variable renewable sources and flexible hydroelectric generation allows not only for demand coverage but also for the optimized use of resources. This behavior suggests that the value of DERs lies not only in their individual contribution but in their ability to integrate within coordinated schemes that enhance their strengths and mitigate their limitations.

From a methodological point of view, the model's validation in an AC simulation environment reinforces the robustness of the proposal. It is not merely a theoretical result but a scheme that respects the physical constraints of the system and can be interpreted within a real operational context. This provides the level of credibility necessary to consider its application in broader scenarios.

Nevertheless, as with any research approach, this work also opens new questions. The incorporation of economic signals, interaction with electricity markets, and communication infrastructure requirements represent natural lines of evolution. In particular, the practical implementation of such architectures will require regulatory frameworks that recognize the value of aggregation and flexibility as essential system services.

In summary, the presented proposal not only validates the technical feasibility of integrating DERs through cooperative schemes but also suggests a paradigm shift in the planning and operation of power systems. Within the context of the energy transition, where decentralization is increasingly evident, moving toward more flexible, scalable, and coordinated organizational models is no longer an option but a necessity.

6. REFERENCES

[1] Agencia de Regulación y Control de Electricidad, "Atlas del Sector Eléctrico Ecuatoriano 2024", vol. 1, p. 109, mar. 2025.

[2] J. Vasquez, J. Guerrero, J. Miret, M. Castilla, L. Garcia De Vicuna, "Hierarchical Control of Intelligent Microgrids", IEEE Ind. Electron. Mag., vol. 4, no. 4, pp. 23–29, Dec. 2010, doi: 10.1109/MIE.2010.938720.

[3] J. C. Sarmiento-Vintimilla, E. Torres, D. M. Larruskain, M. J. Pérez-Molina, "Applications, Operational Architectures and Development of Virtual Power Plants as a Strategy to Facilitate the Integration of Distributed Energy Resources", Energies, vol. 15, no. 3, p. 775, Jan. 2022, doi: 10.3390/en15030775.

[4] E. Ortjohann et al., "Cluster fractal model — A flexible network model for future power systems", in Proc. 2013 Int. Conf. Clean Electrical Power (ICCEP), Alghero, 2013, pp. 293–297.

[5] D. Bytschkow, "Towards composition principles and fractal architectures in the context of smart grids", It - Inf. Technol., vol. 58, no. 1, pp. 3–14, Feb. 2016.

[6] G. Florea, O. Chenaru, D. Popescu, R. Dobrescu, "A Fractal Model for Power Smart Grids", in Proc. 20th Int. Conf. Control Syst. Comput. Sci., Bucharest, Romania, 2015, pp. 572–577.

[7] H. A. Al_Issa et al., "Model of the electric network based on the fractal-cluster principle", IAPGOS, Jun. 27, 2025. [Online]. Available:

https://doi.org/10.35784/iapgos.7380

[8] J. L. Sampietro P. Pico Valencia, "Revisión bibliográfica de sistemas de control para gestión de micro-redes de energía", MASKAY, vol. 8, no. 2, p. 60, Nov. 2018.

[9] M. M. Roozbehani, E. Heydarian-Forushani, S. Hasanzadeh, S. B. Elghali, "Virtual Power Plant Operational Strategies: Models, Markets, Optimization, Challenges, and Opportunities", Sustainability, vol. 14, no. 19, p. 12486, Sep. 2022.

[10] J. C. Sarmiento-Vintimilla, D. M. Larruskain, E. Torres, O. Abarrategi, "Assessment of the operational flexibility of virtual power plants to facilitate the integration of distributed energy resources and decision-making under uncertainty", Int. J. Electr. Power Energy Syst., vol. 155, p. 109611, Jan. 2024.

[11] A. Ulbig, "Operational Flexibility in Electric Power Systems", Ph.D. dissertation, Dept. IT & Elect. Eng., ETH Zurich, Zurich, Switzerland, 2014.

[12] I. Kiriakos F. Zaro, "Designing a Microgrid for a Real Grid Tied PV System", in Proc. 12th Int. Renew. Eng. Conf. (IREC), Amman, Jordan, 2021, pp. 1–11.

[13] P. Molotov, A. Vaskov, M. Tyagunov, "Modeling Processes in Microgrids with Renewable Energy Sources", in Proc. Int. Ural Conf. Green Energy (UralCon), Chelyabinsk, 2018, pp. 203–208.

[14] Manitoba Hydro International Ltd., "IEEE 09 Bus System", Manitoba Hydro International Ltd., Winnipeg, MB, Tech. Rep., May 2018.

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